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ABSTRACT. Analysis of the current state of the theory of multiple particle production at high energy levels and associated peripheral interaction and statistical theories. The relations between the problems of these theories and fundamental theoretical problems, such as the concepts of amplitude and time reversibility, are discussed. The productivity of a statistical approach to multiple particle production processes is noted.

This study has two purposes: first, a discussion of the problems involved /1461*
in the theory of multiple generation, and second, the role and importance of cosmic rays in this problem. Until recently the experimental data obtained in a study of cosmic rays appeared to be valuable both for fundamental problems in theoretical physics and in computations of specific processes. An example of the first is the determination in cosmic rays of an approximate constancy of the total cross-section at high energies. This fact served as a basis for formulating the Pomeranchuk theorem, and then for an entire direction in theoretical physics for investigating the asymptotic properties of the total cross-section. On the other hand, experimental data on multiple generation, (obtained in cosmic rays) stimulated the development of methods for computing specific processes. The statistical theory of multiple generation and the theory of peripheral interactions developed precisely on the basis of experiments in cosmic rays.

However, the situation has now become more complex and it is common to hear the opinion that in the future the role of cosmic rays in the problem of strong interactions will not be as great as in the past. We will endeavor to demonstrate that this opinion is unfounded. We will endeavor to analyze the present-day status of this problem. The analysis is based on the results of the CERN Conference (January 1968) and the Vienna Conference (August 1968).

*Numbers in the margin indicate pagination in the foreign text.

We emphasize two circumstances.

First, the accentuating separation of theoretical studies into two groups: fundamental problems on the one hand, and computations of specific processes on the basis of certain schemes or models, on the other. The center of attention of theoreticians working in the fundamental direction is on problems of the internal closure of the theory. At present their solution does not require experimental data (including data from cosmic rays). In any case, theoretical studies of a fundamental nature are usually not compared with experimental data.

Second, theoretical computations of specific processes of multiple generation are now being made at a different level than before. The use of computers makes it possible to calculate many different characteristics of the process, and do so with great accuracy. These computations are usually compared with accelerator experiments; it is considered preferable not to make comparisons with space experiments. Space data are viewed with respect, giving them due importance. The emphasis is on facts, considered particularly important, which have been established in experiments with cosmic rays and confirmed on accelerators, specifically, such facts as the smallness of the inelasticity coefficients and constancy of the distribution of transverse impulses. However, the respect contained in such statements resembles the comments of a necrologist. At first glance, space experiments again seem to be to one side from the two fundamental directions in theory. This is essentially the basis for the above-mentioned situation.

We will endeavor to demonstrate that in actuality the situation is differ- /1462
ent and the study of cosmic rays and the data and ideas resulting from it have a direct relationship both to the abstract and specific directions in theory. Among the fundamental problems we can define the following.

1. The problem of the asymptotic behavior of the cross-section. Until recently the principle approach here was an investigation of the analytical properties of the amplitude of scattering. However, at the last International Conference on High-Energy Physics this direction[1] was represented relatively

[1]Reference is to a study by Martin [1] and studies similar to it [2].

poorly. On the other hand, there has been an increase in the use of specific schemes of the Bethe-Salpeter equation type. Particular attention has been given to crossing-invariance and unitarity; this has been ahcieved by the successive development of the Bethe-Salpeter equation in the s- and t-channels. The advantage of such schemes is that the mechanism of the process can be seen clearly.

In particular, it was demonstrated that the cross-section of processes caused by a vacuum singularity evidently decreases slowly with energy E_L. The regime $\sigma \sim E_L^{0.02}$ (Chu [3]) or $\sigma \lesssim (\ln \ln E_L)^{-1/2}$ (Royzen [4]) have been discussed. It was also made clear that the energy region in which the problem of asymptotic behavior arises is very distant and, for example, is situated at $\sqrt{\ln \ln (E_L/E_0)} \gg 1$, where E_0 is the order of mass of a nucleon, that is, is virtually unattainable. The remoteness of the asymptotic behavior became clear to the use of a specific scheme; in an analytical approach this remoteness could not be manifested.

Both circumstances, the weak dependence on energy, and more importantly the remoteness of the region of stabilization of an asymptotic regime, transform this problem into one of an academic nature. The experimental study of the asymptotic regime, even in cosmic rays, possibly is virtually unachievable. Nevertheless, the region of "practical" asymptotic behavior is still important; there the difference between $\sigma \approx$ const, $\sigma \sim E^{-0.02}$ and $\sigma \sim (\ln \ln E)^{-1/2}$ is not important and the guiding vacuum singularity can be considered simply as a Pomeranchuk pole. Thus, the entire energy scale can be broken down into four intervals:

1) low energies: $E/E_0 \lesssim 1$;
2) preasymptotic region $E/E_0 \gg 1$ (but $\ln (E/E_0) \lesssim 1$);
3) practical asymptotic behavior $\ln (E/E_0) \gg 1$ (but $\ln \ln (E/E_0) \sim 1$);
4) actually feasible asymptotic behavior, where $\sqrt{\ln \ln (E/E_0)} \gg 1$.

2. There is vigorous discussion of the problem of locality of the interaction, causality and Lorentz invariance. Here as well, one can note a return to specific schemes based on Lagrangians or Hamiltonians. There is a new trend here as well. Earlier it was assumed that the amplitude, obtained as the

solution of some dynamic equation, should describe the process completely and unambiguously. The difficulty arising in this approach is well-known.

Now other possibilities are being analyzed; they were discussed in a review report I. Wightman [5][2]. In a comparison of the amplitude and the observed values additional procedures are introduced which are not involved in the initial equations. Essentially, this involves a revision of the concept of amplitude and its observability. There is hope that by this approach it will be possible to overcome the basic difficulties in theory and divergence. We will give particular attention to this problem, since despite its abstractness, it is the closest to the problems discussed in the physics of cosmic rays.

Now we will return to the specific direction in the theory of strong /1463
interactions. Until recently in both experimental and theoretical respect it was primarily the simplest processes with a small multiplicity which were investigated: elastic scattering, binary reaction, diffraction generation, etc. At high energies, (even those in accelerators) they constitute a small fraction of all processes. Only now this interest is beginning to shift in the direction of a similar detailed study of fundamental processes with high multiplicity; these naturally are of fundamental interest in the study of cosmic rays.

A report by Chan [7] was devoted to a review of these studies. For the most part, reference was to a multi-peripheral "Regge" model with exchange both by a vacuum Reggion and by pions (to be more precise, pion Reggions).

"Regge" multi-peripheral diagrams do not differ in ordinary appearance from ordinary Feynman diagrams. The difference arises in righting the matrix element: in place of the propagator of the internal line of a virtual quantum, one compares a signature factor of the type

$$D(k^2) \to \frac{\pi}{2\mathfrak{M}^2 \sin \frac{\pi}{2} \alpha_i(k^2)}, \qquad (1)$$

[2]Similar considerations, in even clearer form, are set forth in a study by Faynberg [6].

where k^2 is the square of the imparted 4-impulse (in elastic processes it is most common to use the notation $k^2 \equiv -t$); $\alpha_i(k^2)$ is the pole trajectory; for a vacuum Reggion $\alpha_v(k^2)$ has the form $\alpha_v(k^2) = l_0 - \frac{k^2}{\mathfrak{M}^2}$. $l_0 = 1$ for a pion Reggion $\alpha_\pi = -\frac{1}{\mathfrak{M}^2}(m_\pi^2 + k^2)$, $\mathfrak{M}^2 = -\frac{d\alpha}{dk^2}$ is the slope of the pole trajectory. The parameter $\mathfrak{M}^2$ is presently estimated at $\mathfrak{M}^2 \approx$ 1-10 GeV^2. In the case of small values $\alpha(k^2) \ll 1$, expression (1) is transformed into an ordimary propagator.

In addition to replacement of the propagator in the matrix element of Reggion diagrams, another factor appears: a polynomial, or to be more precise, a Legendre function of the order of $\alpha(k^2)$: $P_{\alpha(k^2)}(Z_t)$. The argument of the

$$Z_t = \frac{(s_1 - m^2 + k^2)(s_2 - m^2 + k^2) - 2k^2(s - 2m^2)}{[(s_1 - m^2 + k^2) + 4m^2k^2]^{1/2}[(s_2 - m^2 + k^2)^2 + 4m^2k^2]^{1/2}} \qquad (2)$$

where s_1 and s_2 are the squares of the "masses" of condensations connected by the considered line, s is the square of energy of colliding particles in strong interaction, m is the mass of colliding particles (here assumed to be identical).

This factor plays an important role if $|Z_t| \gg 1$ and $\alpha(k^2)$ is not small. Then it is equal to $\sim Z_t^{\alpha(k^2)}$ and determines the asymptotic behavior of the energy amplitude. In the case of elastic scattering $s_1 = s_2 = m^2$ and formula (2) is transformed to

$$Z_t = 1 - \frac{2s}{k^2 + 4m^2} \qquad (3)$$

and accordingly, $|Z_t| \gg 1$ if the energy s is great, that is, if $s \gg k^2 + 4m^2$.

However, in the case of inelastic processes the condition $|Z| \gg 1$ is satisfied only in a small part of the phase space. In most of the phase space region (for the most typical inelastic processes, whose multiplicity is close to the mean) the value $sk^2/s_1 s_2 \sim 1$ and accordingly $|Z_t| \sim 1$ even at high /1464
energies. In this case the factor $P_{\alpha(k^2)}(Z_t)$ ceases to play any significant role[3].

[3]Here we will not discuss the problem of the behavior of "subtraction" and daughtor trajectories for the case of inelastic processes. However, it is

When this is taken into account it becomes clear (as mentioned in Chan's report) that in inelastic processes exchange with a vacuum reggion is accomplished in a small region of phase space. This exchange is not decisive, standing out in comparison with all other holes for which $\alpha(0) < 1$, and therefore makes a small contribution to the cross-section. It can describe specific processes with a relatively small multiplicity.

The principle contribution to an inelastic cross-section is by exchange by mesons. However, in this case both of the modifications discussed above, associated with the "Regge" transformation of a pion, that is, taking into account motion of the pion pole, are unimportant and the multiperipheral model becomes a special case of the Bethe Salpeter equation [8].

It should be noted that these properties of inelastic processes were also established eariler in [9, 10], devoted to an analysis of interactions in cosmic rays. Thus, one can note with satisfaction the closeness of points of view.

It is important to note one other circumstance. In a detailed computer construction of diagrams of the multipheral type (Chan [7], Pignotti [11]), the authors conclude that there is need for so-called "clusterization". This term means a joining of generated particles into groups (or clusters) connected to one another by single-quantum exchange. The mass of such clusters is of the order of 2 GeV and above. The argument for clusterization in both theoretical considerations (the need for taking into account the strong interaction of secondary particles in the final state[4] as well as practical considerations (without allowance for this effect it is impossible to attain any agreement between computations and experiments with accelerators). Moreover, it is assumed that the particles belonging to one cluster are distributed almost isotropically in its rest system.

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[3][continued from page 5] important that under the condition $|Z_t| \sim 1$; $sk^2/s_1s_2 \sim 1$, the statement made is also correct when daughtor trajectories are taken into account.

[4]Similar considerations have been expressed before in relation to the fireball problem [12].

Thus, one obtains a fireball model with properties which have already been considered many times in cosmic ray physics [13, 14]. The clusters in essence in no way differ from the "condensation" forming during the central statistical interaction of virtual quanta. In this connection the problem again arises: can fireballs be observed at accelerator energies?

The theoretical computations of Akimov and Royzen [15] show that already at an energy $E_L \sim 30$ GeV there should be processes of the fireball height, although with a small cross-section, whereas at an energy $E_L \sim 70$ GeV processes with the formation of one fireball should make a substantial contribution to the cross-section.

Experimental attempts at the detection of fireballs at accelerator energies have already been undertaken in the studies of Krish and Orir (these studies were described in a review report by O. Chizhevskiy at the CERN Conference [11]), as well as in studies by Zhdanov, Tret'yakova and Chernyavskiy [16]. Until now only preliminary data have been obtained, but they can be regarded as weighty evidence in support of the fireball hypothesis. As we see, in this case as well there are no descrepancies between cosmic ray physics and accelerator data.

The use of the statistical theory in accelerator experiments have assumed considerable importance not only in the "clusterization" problem, but also in connection with binary processes (elastic scattering at large angles), as well /1465
as in connection with the problem of the spectrum of masses of generated particles.

Thus, specific theoretical studies are based on two ideas which have once again been taken from cosmic ray physics or at least initially arose in cosmic ray studies: in statistical theory (sometimes with hydrodynamics taken into account) and in the theory of peripheral interaction. In this connection it is now fitting to analyze once the fundamental principles of statistical theory. Statistical theory has two systems of axioms: classical and quantum. In the classical formulation of statistical theory the colliding particles are regarded as "drops" of a continuous medium of limited extent (dimensions of the order of $\hbar/m_\pi c$). In this case the initial form of the particles and its size (of the order of $\hbar / m_\pi c$), are stipulated, whereas in the hydrodynamic theory the equation of state in the form $p = c^2 \varepsilon$ is also stipulated (where p is pressure, ε is energy density, c is the speed of sound). The interaction cross-section in this case is assumed to be equal to $\sigma \approx (\hbar / m_\pi c)^2$ and is not dependent on energy. The number of particles is finally determined by the growth of entropy in the interaction process. The latter point is important to emphasize because this is associated with time irreversibility, being a highly important characteristic of the process.

In the Landau hydrodynamic theory entropy increases only in the process of shockwave propagation. However, it is possible to clearly define the shockwave stage from the escape divergence stage only in the case of high energies and only when viscosity is neglected. In the case of lower energies the formation of particles (and the growth of entropy) occurs during the entire process. In this connection it is fitting to recall the study by Pomeranchuk [17], which has been forgotten to everyone's loss. In this study it was assumed that the volume in which equilibrium is established must be understood as the combined volume of all the generated particles. As a result, within the framework of a purely statistical (but not hydrodynamic) formulation, but taking into account (in contrast to the Fermi theory) the strong interaction of secondary particles, their number is found to be about $n \sim \kappa E_c$, where E_c is the energy spent on pionization in central statistical interaction, κ is a factor of the order of μ_π^{-1}.

In the study by Pomeranchuk no allowance was made for the energy spent on accelerating elements of the volume as a result of hydrodynamic effects. Accordingly, in the case of high energies, this conclusion is incorrect. For this reason, everyone discarded the Pomeranchuk approach (evidently, including the author himself). However, in the case of not very high energies the Pomeranchuk study has a field of applicability. Precisely in the case of collision among nucleons it should be correct up to multiplicities $n_s \lesssim 10$. In the case of higher n_s hydrodynamic acceleration begins to exert and effect, and here one must procede to a hydrodynamic description. This criterion can also be found from hydrodynamic theory if it is assumed that hydrodynamics must be used when the mean (4-dimensional) velocity U_0 becomes great,

($U_0 \approx$ 2-3). Thus, in the case $n_s \sim 10$ be multiplicity must be given by the formula $n_s \sim \kappa E_c$, regardless of the equation of state (which, in particular, is important for fireballs). The correctness of this assertion is supported by the fact that when $E_L \approx 25$ GeV experiments show that in actuality $\langle n_s \rangle \approx \left(\frac{E_L}{E_0}\right)$, where $\alpha \approx 0.46$-0.5 and only when $n_s \approx 100$ GeV does a different regime set in $\langle n_s \rangle \sim \ln(E/E_0)$ or $\langle n_s \rangle \approx (E_L/E_0)^{1/4}$ [18].

With these considerations taken into account, there is no longer any question why at high energies there can be a Landau-Fermi multiplicity $n_s \sim E_L^{1/4}$ corresponding to the equation of state $p = 1/3\varepsilon$, and at low energies, a Heisenberg multiplicity: $p/\varepsilon \to 0$. In actuality, what is involved here is not a change in the equations of state, but in an adequate allowance /1466 for the interaction of secondary particles during their flight.

Another characteristic feature of the statistical process is its duration. The light time of an intermediate state must be much greater than the collision time (the latter is of the order of $\hbar / m_\pi c^2$). In this case accompanying, relatively weak processes (such as electromagnetic radiation, direct formation of muon and electron pairs, etc.) can develop. Their observation, interesting in itself, in theory can at the same time be a "method for measuring" the life time of a compound system [19].

The described classical formulation, adopted in statistical theory, is not entirely satisfactory from the point of view of quantum field theory. An important step in this direction has been taken by Milekhin [20]. It was demonstrated that the principle result of the hydrodynamic theory can be derived from nonlinear field theory by stipulating the appropriate Lagranginans. However, this examination remained quasi-classical, because secondary field quantization was not examined.

In the quantum-field interpretation of statistical theory the basis is an expression for the partial cross-section in the form:

$$\sigma_N \sim |M_N(p_0, p_1, p_2, \ldots, p_N)|^2 \rho_N, \tag{4}$$

where ρ_N is the statistical weight; M is a matrix element. The fundamental assumption essentially involves the hypothesis that the matrix element is a smooth function of its variables, less pronounced than ρ_N.

A further step was taken in studies [21, 22]. It was demonstrated that if the matrix element is factorized, that is, if it is represented in the form

$$M_N(p_0, p_1, p_2, \ldots, p_N) = \prod_i^N M(p_0, p_i), \tag{5}$$

(where N is the number of secondary particles, and p_i are their momenta, p_0 are the momenta of the primary particle), by selecting relatively simple forms of $M(p_0, p_i)$, one can obtain a distribution by multiplicities and other characteristics of the process corresponding to some classical variant of statistical theory.

However, it is important that not all the characteristics can be determined. Specifically, it was later demonstrated [23] that in order to ensure a constancy of the cross-section it is necessary to stipulate an extremely strange dependence between the matrix element and energy, a dependence of the type $M \sim \exp(-\sqrt{\varepsilon})$, which is very difficult to justify from the point of view of quantum-field theory.

The physical essence of this difficulty is as follows. In statistical theory the condition of normalization in intermediate state is important. Specifically for this reason factors of the type exp(-2M/T) appear; they determine a small fraction of the heavy particles, the smallness of scattering by the angle $\theta_c = \pi/2$, etc. In modern quantum-field theory this conditon corresponds to the existence of a so-called half -- S-matrix of a $S(t_1,t_2)$ -- unitary operator describing the development of the system during a limited time interval from t_1 to t_2. The admissibility of such a description is extremely questionable.

Further difficulties arose in attempts to apply statistical theory to scattering at large angles. It was found that for a rigorously determined initial energy the statistical description in general could not be represented in ordinary quantum-field form. The most critical effect here was the so-called

Erikson fluctuation [24] (random fluctuations of the cross-section with small changes in energy or angle): if a formula of the type (4) is used as a point of departure, they must be present; however, in a real statistical process they should not exist. /1467

The fact is, that in statistical theory we do not deal with the amplitude itself (or a matrix element), but with its averaged values (for phases, which is equivalent to averaging for energies). In general, an averaging procedure is not contained in quantum-mechanical computations and is an additional condition. The physical reason for averaging by phases in statistical systems is the high sensitivity of phases to external effects, the instability of these phases characteristic for truly statistical processes. Even in significant external factors in such systems lead to a phase in stability, and in the experiment values which are always averaged by phases are observed.

In dynamic (not statistical) processes the phases of different waves may be randomly scattered in the range from 0 to 2π, but have but a slight sensitivity to external factors. Averaging does not occur for such phases and they can be observed experimentally (the phases are usually manifested in interference effects). This most important difference between dynamic and statistical processes was traced in the model problem of scattering on a random potential [25]. Finally, the fundamental problem of reversibility of the process assumed a critical importance in this connection; in statistical theory irreversibility is a necessary element, whereas in quantum theory it is absent. This is one of the most interesting and important problems in statistical theory.

The problem arises: if the statisical process corresponds literally to actuality and at the same time it cannot be described in terms of amplitude, then is the approach based on the S-matrix and amplitude really universal? This problem obviously has something in common with the fundamental problems already discussed.

It can be seen from what has been said above that the use of a statistical approach in the interpretation and computation of processes of multiple generation, as well as scattering at large angles, is not only productive, but also gives rise to a number of interesting and fundamental problems. Accordingly, a further study of the properties of statistical processes in the interaction of particles in cosmic rays and even the simple demonstration of the fact of existence of long-lived intermediate states of statistical and compound systems developing in accordance with statistical and hydrodynamic theory, would be of exceptional interest. For example, the problem of the existence of such systems could arise in a study of the direct electromagnetic generation of particles already discussed above.

Thus, the physics of cosmic rays has by no means exhausted itself in the field of study of strong interactions. The physics of cosmic rays contains ideas which have not yet been fully used in theory and which retain timeliness relative to fundamental problems. Naturally, the experimental data obtained in cosmic ray studies, taking into account the present-day high requirements on accuracy characteristic for an accelerator experiment, can be regarded only as indicative. However, these indications are of very great value for planning accelerator experiments. It can be said that cosmic ray physics is directing present-day accelerator experimentation with respect to the multiple generation problem.

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